ELECTRON BEAM ENABLED SURFACE COMPOSITION, CHARGE, AND ADSORBED GAS DETERMINATION

Thomas George
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 302-306
Pasadena, CA 91109
818-354-6017
Thomas.George@jpl.nasa.gov

Jason Feldman
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 302-231
Pasadena, CA 91109
818-354-5491
Jason.Feldman@jpl.nasa.gov

Nathan Bridges
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 183-501
Pasadena, CA 91109
818-393-7799
Nathan.Bridges@jpl.nasa.gov

Martin Buehler
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 302-231
Pasadena, CA 91109
818-354-7799
Martin.Buehler@jpl.nasa.gov

Howard Rockstad
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 302-231
Pasadena, CA 91109
818-354-0661
Howard.Rockstad@jpl.nasa.gov

Jaroslava Wilcox
Jet Propulsion Laboratory
4800 Oak Grove Drive, M/S 302-231
Pasadena, CA 91109
818-354-3556
Jaroslava.Wilcox@jpl.nasa.gov

Abstract—The Human Exploration and Development of Space Roadmap calls for Human Missions to Mars and other planets in the 2010 to 2023 timeframe. This paper describes a proposal written in response to the Announcement of Opportunity (AO99-HEDS-01) for definition studies preparing for the human exploration of Mars. Specifically, the proposal addressed the call for the development of innovative instrument concepts aimed at studying soil, dust, and environmental interactions for 2005 Mission Opportunities. The objective of the proposed study was to determine the feasibility, under simulated Martian ambient conditions, of a suite of miniature instruments performing correlated measurements of sample surfaces. A novel Atmospheric Electron X-ray Spectrometer (AEXS), an optical microscope capable of producing low magnification images, an electrometer, and a fiber optic oxygen sensor fitted with a resistive heater comprised the proposed instrument suite.

The scope of the proposed work included laboratory testing and characterization of prototype instruments making up the proposed instrument suite. Laboratory experiments would utilize instruments in development at JPL combined with modified commercial off-the-shelf instruments. Suite instruments currently being developed by JPL are the AEXS (funded by the NASA PIDDP program) and the electrometer (funded by the MECA-HEDS Mars '01 program). The primary criteria for selection of commercial components would be their miniature size and ruggedness. Since the investigation will be conducted under cost constraints, the emphasis was on using miniature instruments, which could be readily adapted to meet flight requirements.

The above tests would result in the definition of a potential '05 instrument suite addressing issues of surface state mineralogy, oxidant chemistry, electrostatic charge, and adsorbed chemical species that could potentially affect machinery as well as the human body. The instrument suite would be capable of performing the following in situ analysis of the same soil or dust sample:
- High spatial resolution surface elemental composition correlated with optical imaging;
- Electrostatic charge;
- Evolution oxygen from sample heating.

The presence of significant quantities of dust on Mars has been well established by previous telescopic observations, orbital reconnaissance, and landed missions. In fact, the Martian surface has often been obscured by planet-wide dust storms lasting several months. The effect of terrestrial dust on humans has been relatively well studied. The National Institute for Occupational Safety and Health (NIOSH) has

established guidelines for maximum exposure levels to dust containing silica particles, known to cause serious or even fatal respiratory disease. It is also well known that particles less than 1 mm in size can acquire charge. On Earth, a difference in the polarity of this charge has been observed as the particle size varies. The particle size effect is not known on Mars, but can potentially be found if the proposed instruments are eventually flown. In extreme cases, the electrostatic force on saltating particles can exceed the gravitational force.

The adhesion of Martian charged particles could affect humans and hardware adversely, jamming joints on spacesuits, covering faceplates and optical devices, and discharging onto astronauts or equipment. It is believed the dynamics of settling dust, especially after a dust storm, could cause changes in the charge state of the Martian surface. Finally, oxidizing species are speculated to be present in the Martian soil. Evidence for the possible presence of these soil oxidants was obtained from the Viking Gas Exchange and Labeled Release experiments. If indeed such oxidizing species exist, their effect, primarily on the human respiratory tract, could be severe.

The novel electron beam based AEXS is the core component of the proposed instrument suite concept. The AEXS is a miniature non-contact instrument capable of producing a controlled electron beam in the ambient atmosphere. It consists of an electron source that is encapsulated using a microfabricated electron-transmissive membrane. Operated separately, the AEXS employs the electron beam to excite x-ray fluorescence for rapid (less than 1 minute) determination of the surface elemental composition via energy dispersive analysis. Surface morphology and elemental composition information can be obtained by operating the AEXS in conjunction with the optical microscope. The electrometer will be integrated into the instrument foot. The foot will also contain calibration standards for the AEXS and will serve to accurately locate the AEXS relative to the soil or mineral sample. The electrometer will measure the electrostatic charge present on the mineral and soil samples and will be located in the post-membrane ionization region of the AEXS. This configuration allows for the neutralization of accumulated charge using ions generated by the AEXS electron beam. The rapid charge neutralization process will enable multiple, precise measurements of surface charge. The electrometer will also provide electric field gradient measurements above the surface. The miniature

fiber-optic oxygen sensor will be capable of detecting oxygen desorbed from the surface by a resistive heater. A highly sensitive (~ 1 ppb) commercial sensor will be procured. One such sensor manufactured by Ocean Optics Inc. operates on the principle of quenching of the fluorescence of a ruthenium organic luminophore. The ruthenium complex is coated as a sub-micron film on the end of a fiber and fluoresces at approximately 600 nm upon excitation by a blue light emitting diode (peak output 470 nm). The collision of oxygen molecules with the fluorophores in their excited state leads to quenching of the fluorescence via a non-radiative transfer of energy.

The primary advantage of this instrument is that there is no interference from either moisture or CO_2. The strategy would be to first measure the oxygen background from the ambient atmosphere enclosed by the sample chamber (over the sample). A miniature resistively heated probe mounted in the instrument foot would then heat a small region of the sample surface to several hundred degrees Centigrade. The oxygen (if present) will be desorbed from the surface by heating and then detected by the fiber optic oxygen sensor. Thus, this measurement will not only provide quantitative estimates of the adsorbed oxygen, but also the temperatures at which the oxygen is desorbed, information which would help to identify the nature and abundance of oxidants that could be hazardous to humans and equipment.

TABLE OF CONTENTS

1. INTRODUCTION

Five centuries after the discovery of the New World by Christopher Columbus, NASA has embarked on a challenging endeavor to put humans on Mars. The planetary environment on Mars is still poorly understood and the gaps in our knowledge need to be filled before we can risk human lives to the potential hazards that might exist on Mars. For example, the dry, dusty environment of Mars poses several potential hazards as shown below in the illustration (Figure 1) developed by the Mars Environmental Compatibility Assessment (MECA) project.

In order to develop a fuller understanding of the nature of the hazards faced by future astronauts, it is important to develop suites of instruments that can produce correlated measurements rather than individual instruments making measurements in isolation. This proposal is a small step in that direction, and is aimed at the development of a suite of miniature instruments that can make correlated measurements of the Martian soil and dust to determine the surface mineralogy, nature of the electrostatic charge, and adsorbed oxygen content.

Proposed HEDS instrument Suite Specifications

Mass	1,585 g
Volume	1,067 cm^3
Power	13 W (maximum)

2. OBJECTIVES AND SIGNIFICANT ASPECTS

The aim of the proposed study is to investigate the feasibility and characteristics of a suite of miniature instruments via laboratory experiments conducted under simulated Martian ambient conditions. The proposed suite consists of a novel Atmospheric Electron X-ray Spectrometer (AEXS), an optical microscope capable of producing low magnification images, an electrometer, and a fiber optic oxygen sensor fitted with a resistive heater. The investigations will be conducted in a laboratory setting simulating the ambient Martian conditions with Mars analog soil and rock samples.

The AEXS instrument is currently being developed under a NASA PIDDP program. The electrometer will be a modified version of the instrument being developed for the MECA project. The optical microscope, the resistive heater, and the fiber optic oxygen sensor will be procured commercially.

The ultimate objective of the feasibility and characterization study is the definition of a potential '05 instrument suite (Figure 1) capable of making correlated in situ measurements of surface mineralogy, electrostatic charge, and adsorbed oxygen. The AEXS, first proposed and being developed by JPL [1, 2] is central to the instrument suite and provides a novel technology capable of rapid (< 1 minute) elemental analysis of surfaces via electron-beam excitation of characteristic x-ray fluorescence from surfaces. Previous in situ elemental analysis instruments, such as the Mars Pathfinder Alpha Proton X-ray Spectrometer (APXS) [3] and the Viking Lander X-ray Fluorescence instrument (XRF) [4] used radioactive sources to excite x-ray fluorescence from planetary samples. Both of these instruments had considerably longer spectrum acquisition times (several hours in the case of Mars Pathfinder). The AEXS consists of a miniature electron column isolated from the planetary ambient by an electron-transmissive membrane. An electron beam is generated and transmitted through the membrane to impinge on the sample in atmosphere. Characteristic x-rays are excited and analyzed to determine the sample surface elemental composition as in an electron microscope, without the need to introduce the sample into vacuum.

The area being irradiated by the AEXS will be imaged by an optical microscope at a spatial resolution of 10 μm. The electrometer will provide high dynamic range measurements of the nature and quantity of the charge present on the surface. The fiber optic oxygen sensor will be used to first measure the background oxygen present in the sample chamber and then measure the excess oxygen evolved from the surface via resistive heating. The AEXS, the optical microscope, the electrometer, and the fiber optic oxygen sensor will all be located within the sample chamber (see Figure 3 in Section 2.4) and will therefore provide correlated measurements of the same surface area of the sample on Mars.

2.1 STATEMENT OF HYPOTHESIS: RELEVANCE TO HEDS GOALS

The proposed work seeks to address the hypothesis that correlated in situ measurements performed by a suite of instruments will provide superior information, relevant to HEDS goals, over measurements made by individual instruments operating in isolation.
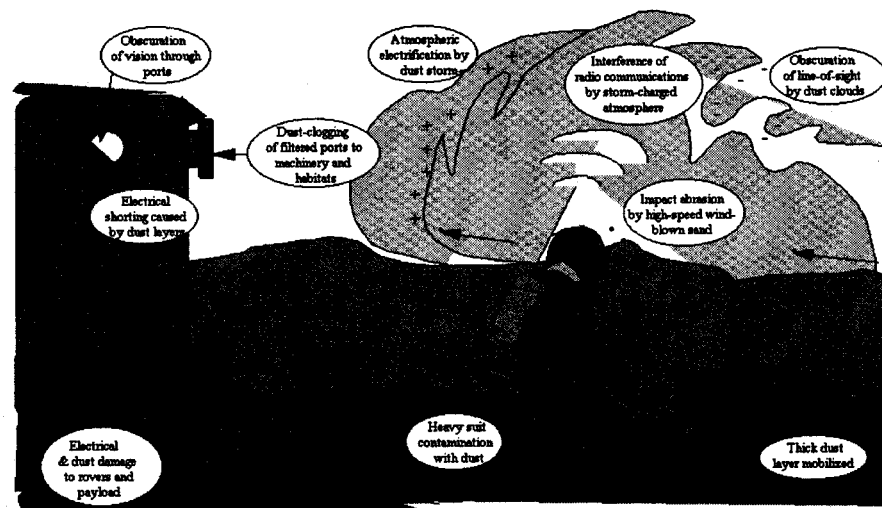
Figure 1. Proposed dust hazards on Mars (developed by the Mars Environmental Compatibility Assessment (MECA) project).

The proposed integrated instrument suite containing an AEXS, a low-magnification optical microscope, an electrometer, and a fiber optic oxygen sensor fitted with a resistively heated probe seeks to identify and characterize potential soil and dust hazards that could be detrimental to humans and machinery. This suite can investigate the following properties of the Martian surface:

2.2 SURFACE STUDIES

Mineralogy—In situ measurements from an AEXS will improve our understanding of the composition of Martian dust and soil due to several advancements over previous instruments:

a. *Small beam size*—The 100-μm to several mm-size beam should be able to determine the elemental composition of specific minerals, something never before achieved on another planet (e.g., the Pathfinder APXS measured a spot ~ 4 cm in diameter). This AEXS capability will be particularly effective when used in conjunction with the low magnification optical microscope capable of identifying 10-μm diameter grains of dust and soil. Elemental analysis measurements will provide important information on the chemical composition of dust and soil particles and help identify potential hazards. Since astronauts could possibly inhale the dust, the presence of oxidants or quartz particles (silicosis) needs to be identified.

Additionally, determinations of the composition of magnetic particles that adhere to pressure suits and equipment may be necessary. Magnetic studies on Mars Pathfinder have indicated that these magnetic particles are probably composed of maghemite (γ-Fe_2O_3), or perhaps titanomagnetite or titanomaghemite, which can be easily differentiated by the AEXS.

b. *Low power and spectrum acquisition time*—These two advancements will allow the AEXS to take multiple readings of dust and soil samples, thereby assessing surface mineralogy and heterogeneity. Alternatively, it could measure several samples in a short amount of time, effectively providing a quick look, petrologic field reconnaissance of a region.

c. *Ability to detect elements down to Z=6 (C)*—The APXS and XRF were limited to $Z \geq 11$ (Na). Detection of C and N will permit the identification of carbonates and nitrates, respectively. Detection of O could potentially allow the oxidation-state of the mineral to be assessed.

d. *Small penetration depth*—The μm-level penetration depth of the AEXS will allow surface elemental composition measurements to be made with minimal mixing effects from deeper material.

Future NASA in situ planetary missions will require increasingly sophisticated analytical instruments while at the same time demanding lower mass and power consumption. Unlike many other proposed instruments, the AEXS meets these generally disparate challenges. It offers the following advantages:

- Short X-ray spectrum acquisition time
- Low energy consumed per acquired spectrum
- Low mass
- Low complexity
- High spatial resolution
- Pristine sample measurement

The short acquisition time and low energy consumption of the AEXS should allow the acquisition of multiple spectra for the same amount of time or energy used by an XRF or APXS for a single measurement. This will maximize the science return, especially for short duration missions or rovers that can only spend a limited amount of time at any one site. The former capability will be especially relevant for missions where environmental conditions limit spacecraft lifetime and rapid in situ sampling is highly desirable. Such sites include the Martian polar regions (limited sunlight). For long rover traverses, it will be important to assess the mineralogy of the dust and soil at a rover stop as rapidly as possible.

In addition to having lower energy consumption, the mass and complexity of the AEXS is less than that of other vacuum-based instruments that provide similar elemental information, such as miniature mass spectrometers and scanning electron microscopes. The electron-transmissive, vacuum isolation membrane of the AEXS negates the need for an evacuated sample chamber and, in turn, sample-handling equipment and vacuum pumps.

Electrostatic charge—In order to ensure the health and safety of exploration crews on Mars, advance determinations must be made of the electrostatic behavior of dust and sand on the surface and in the atmosphere near the surface that the crew will encounter. On earth, dust and sand particles can become charged via triboelectric processes; in extreme cases, the electrostatic force on saltating particles equals the gravitational force [5]. This charging affects surface adhesion, mobility, and local charge-state of the atmosphere. Determining the charge of Martian particles is directly relevant to satisfying the HEDS objective of assessing the interaction between particulates (soil and dust) and humans and machinery. Electrostatically charged particles on Mars could potentially adhere to humans

and hardware with adverse effects, such as jamming of joints on spacesuits, obscuring faceplates and optical devices, discharging of charged particles onto astronauts, transport of particles into their habitat, etc.

It is a well established fact that Mars has dust storms that form in the southern spring or summer, near perihelion, in areas of higher temperature gradients or surface relief. Some of these storms can intensify to become planet-wide and last for a few months. The dust is probably not raised directly by winds, as the threshold friction speed for dust particles is exceedingly high. Rather, dust is probably raised by one or more of the following processes: a) Impact of saltating sand-sized particles, b) dust devils, c) raising of dust by CO_2 desorption, and/or d) saltation of dust aggregates which later break up. It would be of interest for HEDS to determine the duration that the dust remains in the atmosphere after the initiation of a storm and the decline of the atmospheric dust content over the duration. The duration of dust storms is known in a general sense from optical measurements, with the atmosphere clearing after a few weeks or months. The dynamics of settling dust could be understood through several (nearly) instantaneous measurements of surface charge accumulation, using the combination of the AEXS and the electrometer.

Terrestrial measurements have shown significant electric fields in the atmosphere above the surface in fair weather, and much larger fields during dust storms [5]. These observations at a few centimeters to two meters above the surface have also exhibited a strong height dependence of the electric field. Particle charging in aeolian processes is also a factor in the interparticle forces that determine threshold wind speeds at which particles begin to move [6]. Measurements both in Earth's near-surface atmosphere, in laboratory plasma chambers, and in wind tunnel experiments have characterized charge on dust and sand particles [5,7]. Observation of several million electronic charges per grain of sand of the order of 100 microns in diameter is common. (Schmidt, *et al.* [5], find charge-to-mass ratios of 60 µC/kg for 150 µm sand particles, for example.) Various polarity effects under differing experimental conditions have also been observed. For example, Cross [8] has described a particle size dependence of the polarity of the charge. Such a dependence is illustrated in Figure 2 for powder passed through fans making contact with a plastic surface (full curve) and a metal surface (broken curve). As shown by the figure, particles smaller than 200 µm were positively charged, while larger particles were negatively charged.
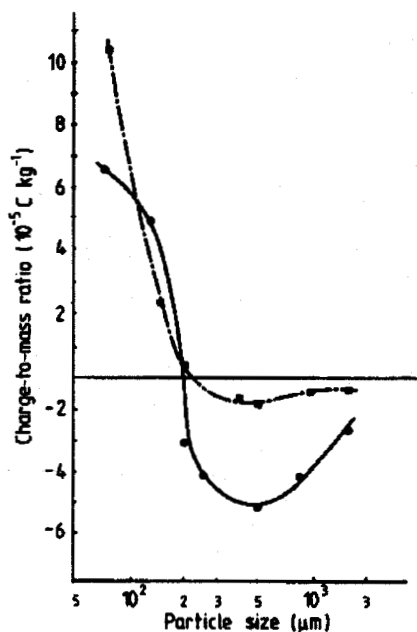
Figure 2. [after *Cross* 1987]. Dependence of charge on particle size for powder flowing through a fan. Solid line: plastic surface; broken line: metal surface.

In contrast with these results, Greeley and Leach [9], in a different context, namely, sand in a wind tunnel, found particles larger than 60 μm were positively charged and those less than 60 μm negatively charged (Table 1). Other wind tunnel experiments have indicated negatively charged surface particles in accumulation regions and positively charged particles in areas of erosion [10].

While quartz (SiO_2) is a common constituent of dune sand on Earth, pyroxene, typically $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$ is the most abundant component of basaltic sand expected on Mars. Table 1 tabulates charges per particle for quartz, pyroxene, and dust for selected particle sizes, for a charge/mass ratio 60 μC/kg, used here in order to provide a rough estimate of charge per particle that may be encountered. An alternative assumption, that a representative charge per particle scales with the particle radius squared as supported by electrostatic considerations [8], leads to larger charges on the small dust particles, as shown in Table 1.

Terrestrial observations of electric fields in the atmosphere above the surface, and of saltating and stationary charged particles, support the importance of electric field and charge measurements on Mars.

The electrometer can be used both to measure variation in atmospheric field with height above the surface, and to measure and compare surface charge in various areas, possibly including particle accumulation and erosion areas.

2.3 EVOLVED GAS STUDIES

Reactivity and its relation to mineralogy—Martian soil is highly oxidizing and capable of destroying organic material, posing potential detrimental effects to the human respiratory system and skin tissue. Organic materials that may be considered for habitats and human-tended machines, such as plastic, rubber, and other polymers, could degrade under prolonged exposure to the Martian environment [11]. Many oxidants that have been proposed to exist on the Martian surface are inherently unstable, making in situ analysis, as opposed to studies of returned samples, highly desirable.

The proposed instrument suite can identify the elemental composition, mineralogy, and volatile oxygen inventory of soils. By determining the composition of many sites on the Martian surface, and at various depths, the instruments will provide data relevant to characterizing soil oxidation-state. For example, with the 100 μm beam of the AEXS, it may be possible to identify ferric (e.g., hematite) and ferrous (e.g., pyroxene) minerals in the soil, thereby providing mineralogical data that can, in turn, be related to reactivity. By using the AEXS in conjunction with the fiber optic oxygen sensor (for detecting evolved oxygen), the proposed instrument suite can be used to identify soil compositions associated with specific oxide chemistries. The fast acquisition time of the fiber optic oxygen sensor (< 1s) relative to traditional methods used to characterize oxidation state (Eh measurement, humidification, adding non-aqueous solvents, etc.), will allow a rapid assessment of the oxidation state of the surface.

Atmospheric Background Measurements—Measurements of the background oxygen concentration in the enclosed atmosphere of the sample chamber need to be made in order to detect the evolution of excess oxygen by heating the soil. The oxygen is detected by the quenching of the fluorescent response of a thin-film ruthenium organic complex excited by a blue LED. Measuring the oxygen species in the atmosphere is also important from another aspect. Strongly oxidizing odd-H and -O species, including H_2O_2, O_3, and HO_2, may be present at the base of the

Table 1. Charges per particle for selected particle sizes

Composition	Density[1] (kg/m³)	Particle size[2] (μm)	Charge per particle (μC)[3] [Q/m = 60 μC/kg]	Charge per particle (μC)[3] [constant Q/a²]
Quartz	2650	80	4.3×10^{-08}	8.0×10^{-08}
Quartz	2650	115	1.3×10^{-07}	1.7×10^{-07}
Quartz	2650	1000	8.3×10^{-05}	1.2×10^{-05}
Pyroxene	3300	80	5.3×10^{-08}	8.0×10^{-08}
Pyroxene	3300	115	1.6×10^{-07}	1.7×10^{-07}
Pyroxene	3300	1000	1.0×10^{-04}	1.2×10^{-05}
"Dust"	2000	2	-5.0×10^{-13}	-5.0×10^{-11}
"Dust"	2000	10	-6.3×10^{-11}	-1.2×10^{-09}

[1]For "dust" the assumed density is somewhat less than that of common clay (montmorillonite = 2500 kg/m³); the dust may consist of a mixture of basalt and clay minerals with nanophase oxides and hydroxides. In assigning a density of 2000 kg/m³, it was also assumed that the dust is porous on the microscopic level.

[2]The particle size entrained by the minimum threshold friction speed on Mars is 115 μm. A common dust particle size on Mars is 2 μm.

[3]Where Q/m is the charge to mass ratio and a is the particle radius. The signs shown here are based on Greeley and Leach [9].

Martian atmosphere in abundances as high as 10^{16} m^{-3} [12]. If present, they will act to oxidize the surface. Determining the abundance and composition of these species in the Martian atmosphere is relevant to addressing the HEDS objectives described in Section i.

The composition of adsorbed chemical species—A number of chemical species may be adsorbed on the surfaces of Martian soil and rock. These include H_2O, OH$^-$, and oxygen radicals (O, O_2, O_3^-). The presence and abundance of these species has HEDS implications similar to those discussed above. For example, the superoxide radical O_2^- is extremely effective at breaking down water and organics. The origin of these superoxides is not well understood and is the subject of some speculation. It is believed that some minerals could serve as superoxides, while many others may simply be surfaces upon which the superoxides reside. Some investigators have proposed that activated halides may serve as superoxidants. This would include those containing chlorine (perhaps halite (NaCl) and sylvite (KCl)), which is abundant on Mars. Polar minerals such as quartz could provide surfaces upon which charged superoxides may reside. These superoxides are expected to be relatively unstable thermally and may release the excess oxygen with a modest increase in temperature (ΔT of ~100K). Other gaseous species that could be desorbed include water vapor, which will be released at temperatures < 350 °C. Evolution of water vapor at temperatures of 350 °C to 500 °C in the Viking GC-MS indicates other forms of hydration as well. For SNC-like compositions, studies indicate that structural dehydration of some minerals, such as gypsum, can occur at approximately 150 °C to 350 °C. Higher temperatures can cause dehydration of other minerals as well as decarbonation, desulfonation, etc. The extremely high selectivity of the fiber optic oxygen sensor should help in the detection of the evolved oxygen over the rest of the background (Table 2).

2.4 INSTRUMENTS TO COMPRISE SUITE

The instrument suite (Figure 3) will be composed of the following components:

Sample chamber—The sample chamber will be a small hemispherical chamber (approximately 2 cm diameter) which is open to the Mars ambient at the base. A flexible contact ring along the perimeter of the sample chamber will provide a sealing surface with the Martian sample, minimizing the exchange of gas within the sample chamber with the outside atmosphere. The contact ring has a spring/bellows suspension, which will bring the chamber into direct contact and close alignment with the surface. The sample chamber will also provide for the incorporation, in the desired configuration, of the various instruments that make up the suite. The flight version of the instrument suite will depend on a deployment mechanism to bring the sample chamber and associated instruments in contact with the Mars surface.
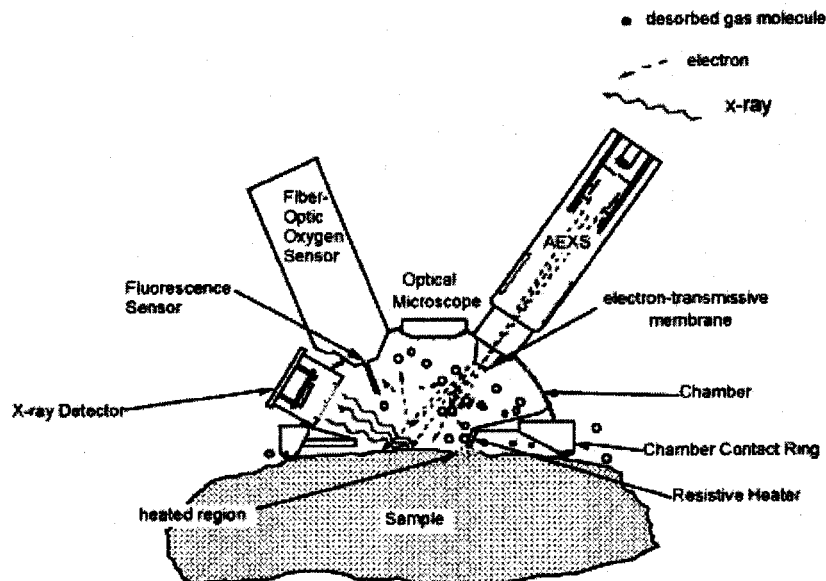
Figure 3. Schematic of the proposed instrument suite mounted to the sample chamber. Shown are the integrated AEXS, low-magnification optical microscope, electrometer, and fiber-optic oxygen sensor with a resistive heating probe.

Atmospheric Electron X-ray Spectrometer (AEXS)—
The AEXS will be the primary component of the proposed instrument suite and will be used to *determine the elemental composition of the surface being studied.* Additionally, the electron beam the AEXS generates in the ambient atmosphere will provide neutralizing ions for electrometer studies.

The proof-of-principle for the AEXS was recently demonstrated at JPL (Figure 4). The AEXS is currently being developed under NASA PIDDP funding for performing in situ elemental analysis of planetary surfaces. The analysis is performed by detecting electron-beam excited x-ray fluorescence in a manner similar to modern electron microscopes. The key enabling novelty of the instrument is that the vacuum of the electron column is isolated from the planetary atmosphere by a microfabricated electron-transmissive membrane (Figure 5), so that the sample does not need to be drawn into a vacuum region for analysis. The AEXS instrument is shown schematically in Figure 6, and consists of an evacuated electron column capped by the thin membrane, an x-ray detector, associated power supplies, and drive electronics. A high-energy (in excess of 10 keV) electron beam is transmitted through the membrane and generates characteristic x-rays from a planetary sample. Unlike in the

laboratory electron microscope, non-conductive mineral samples do not need to be coated with a conductive film, because electron-induced ionization of the atmosphere provides a return path for accumulated charge. The x-ray spectrum is acquired by an x-ray detector, and the data is processed using standard energy dispersive x-ray (EDX) analysis techniques to obtain the elemental composition of the irradiated spot.

As shown in Table 3, the AEXS offers improved performance in comparison to other "state-of-the-art" x-ray-based elemental analysis techniques such as the Alpha Proton x-ray Spectrometer (APXS) and a proposed X-Ray induced Fluorescence (XRF) technique. The AEXS has a considerably shorter x-ray spectrum acquisition time and (consequently) lower energy consumption per acquisition. By also using a thin membrane for the x-ray detector window, the AEXS may be able to detect light elements such as C, N and O, potentially allowing a complete stoichiometric determination of the mineral. The AEXS is amenable to miniaturization, and in addition, due to its ability to focus electrons, has a much higher spatial resolution (irradiated spot size < 1 mm) than is feasible for other techniques.
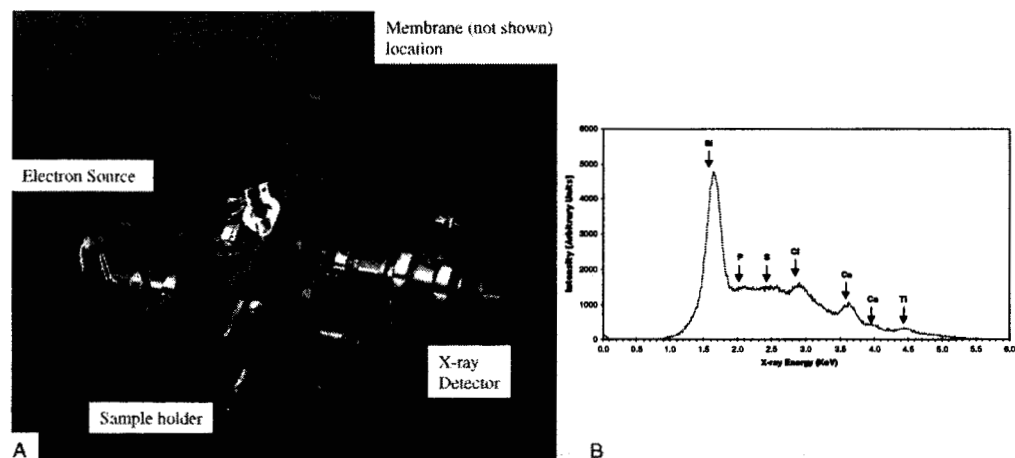
Figure 4. (A) Laboratory test setup for Atmospheric Electron X-ray Spectroscopy, (B) X-ray fluorescence spectrum (raw data) of a JSC Mars-1 (JSC-1 Mars Regolith Simulant) sample obtained in the setup by 5.5 keV electron-beam excitation in air.

Figure 5. Scanning electron micrograph of the microfabricated, electron-transmissive membrane showing the silicon frame (A) and the 200-nm-thick SiN membrane (B).
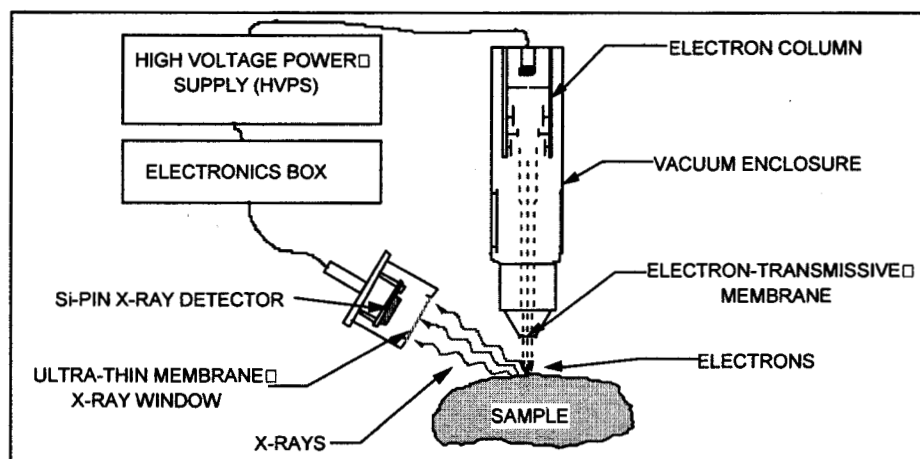

Figure 6. Schematic diagram showing the components of the AEXS.

Table 2: Expected Desorption vs Temperature Characteristics of Martian soil

Temperature Range (K)	Desorbed Species
< 600	Loss of adsorbed water and oxygen radicals from "superoxide" species such as KO_2, ZnO_2, $Ca(O_2)_2$, MnO_2, and H_2O_2. Since these superoxide compounds are expected to be thermally unstable, oxygen radicals can probably be released by heating to only 100 K above ambient (i.e., to around 300 K).
400–500	Dehydration of gypsum ($CaSO_4 \cdot 2H_2O$) and epsomite ($MgSO_4 \cdot 7H_2O$) (loss of structurally bound water in these minerals).
800–1000	Dehydration of saponite ($(Mg,Fe)_3(Al,Si)_4O_{10}(OH)_2(0.5Ca\ Na)_{0.3} \cdot 4H_2O$), serpentine ($Mg_3Si_2O_5(OH)_4$), and chlorite($MgSO_4 \cdot 7H_2O$).
900–1100	Decarbonation of calcite ($CaCO_3$) and dolomite($CaMg(CO_3)_2$) (loss of structurally bound CO_2, forming $CO_2(g)$).

Table 3: Comparison of the AEXS with other in situ x-ray fluorescence instruments

Specification		AEXS (prototype)	XRF (proposed) [2]	APXS (flight) [1]
Mass[1]		970 g	1000 g	570 g
Source[2]	Excitation particle	Electrons	x-ray photons	α-particles
	Flux	6×10^{13} /s (10μA)	2×10^{12} /s	2×10^{9} /s (50mCi)
	Power	5 W (current HVPS)	13 W	0.34 W
Excitation efficiency[3]	X-ray photons emitted per particle	5×10^{-6}	1.4×10^{-5}	5×10^{-6}
	Geometrical efficiency	$> 10^{-4}$	10^{-6} to 10^{-5}	10^{-4}
	X-ray photons per second	$> 2 \times 10^{4}$	10^{2} to 10^{3}	~ 1
Spectrum acquisition[4]	Acquisition time	10 seconds	5 minutes	10 hours
	Energy per acquisition	50 J	5,000 J	10,000 J
Spot size[5]	Controlled by beam focusing	10^{-2} to 10^{-4} cm^2 (spot size from 100 μm to several mm)	~ 4 cm^2 2 cm working distance)	~ 20 cm^2

[1] For the AEXS, the mass is predicted for the prototype system (including HVPS and all electronics), whereas for the APXS and the XRF the masses are for the flight and proposed-for-flight instruments, respectively. For the flight AEXS the mass and power consumption can potentially be decreased by a factor of 2 through optimization and HVPS miniaturization. Note that XRF instruments often appear in an XRF/XRD combination.

[2] For the AEXS most of the power is consumed by the HVPS; optimization of the flight instrument optimization should reduce this figure to about 2W. For the XRF[2] the primary current is high (0.3A) to make up for losses due to the low (10^{-3}) electron/x-ray conversion efficiency; the accelerator column consumes in excess of 9W vs. 4W for the emitter.

[3]The excitation efficiency is the product of the fluorescence efficiency and the probability that the x-rays escape from the sample. The estimates are for Si samples irradiated by 30keV electrons by the AEXS, a Au target for the XRF, and for 5MeV α particles for the APXS. The geometrical efficiency was estimated for each instrument assuming the same, approximately 4 mm^2 x-ray detector area, about 2 cm working distance for the AEXS and XRF[2], and 4 cm for APXS[1].

[4]The X-ray sampling speed for AEXS is detector-limited to ~2×10^{4} counts/s (at 2 cm working distance).

[5]The spot size depends on the electron beam energy and on the electron scattering in the membrane and atmosphere

Optical Microscope—A candidate commercial optical microscope procured for laboratory testing would be the Hitachi Denshi America, Ltd. miniature remote head, interline transfer CCD camera (Figure 7) connected to a Matrox frame grabber computer board. The extremely compact remote-imaging head (12.6 mm diameter by 41.5 mm long) will facilitate integration of the optical microscope into the instrument sample chamber. *The optical microscope will provide low-magnification optical images (~10 μm resolution) of the observation area.* These images will provide important contextual information on the particle size and morphology of the dust and soil samples being examined.

Figure 7. Miniature optical microscope for laboratory testing.

Electrometer—The electrometer will be integrated into the instrument "foot" (the base of the sample chamber). The foot is necessary for calibration and accurate location of the AEXS, and will be part of a deployment mechanism that will serve to deploy the AEXS and the electrometer at a fixed distance from the surface under examination. *The electrometer will measure surface charge.*

The electrometer will be based on the induction electrometer designed at JPL [13,14] for the MECA project. A photo of the packaged MECA electrometer, incorporating six electrometer sensors and accompanying circuitry, is shown in Figure 8. The MECA electrometer in the photo includes five sensors designed for triboelectric studies and one electric field sensor; the electrometer envisioned for the laboratory testing will consist of four to seven electric field sensors based on the MECA design. With a 12-bit A/D converter, the dynamic range of each sensor is about 4000. Multiple electrometer sensors will be included for two purposes. Two sensors will be set at different sensitivities to provide the broadest possible measurement range. For example, one sensor may be scaled to detect as few as 1000 electronic charges while another may be scaled to detect a million and more electronic charges. Other sensors will be coated with various insulators,

permitting determination of charged particles adhesion to a given insulator. Such information will also benefit HEDS.

Mass and volume for the electrometer and electronics will depend on how they are incorporated in the overall instrument design, and are conservatively anticipated to be less than 10 g and 5 cm^3, respectively. Power consumption is estimated to be 250 mW, but can be much less if a clean ± 5 V source is available. A data rate of the order of 2 bytes/sec is anticipated although the electronics will allow much higher rates.

The induction electrometer gives relative charge or field measurements. Figure 9 shows the circuit for this electrometer in a configuration with the electric field sensor near a charged soil surface. In this configuration the sensing electrode and soil surface have a capacitance C2. The instrument comprises a capacitive divider where C2 is the field sensing capacitor and C1 is a reference capacitor. The point between the capacitors is connected to the positive terminal of the first stage amplifier operated in a low-gain follower mode. The sensing electrode is protected by a driven guard that is connected to the negative terminal of the first stage amplifier. A second operational amplifier U2 provides additional amplification. To operate the instrument, capacitor C1 is first discharged with solid-state switch S1, which has very low leakage. The sensor is then drawn away from the soil surface. If the soil surface is charged while the atmosphere at the new position is neutral, the field sensed by the sensor electrode will change and charges will flow in the capacitor divider circuit, giving a potential V1, which is then amplified to give the output VA.
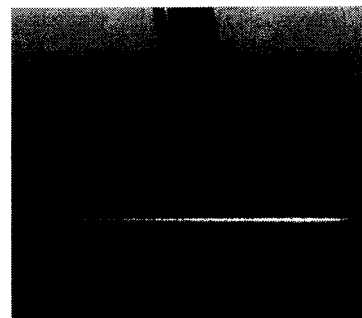

Figure 8: Photograph of the MECA electrometer described in the text. In addition to five electrometer sensors, an ion trap is also shown.
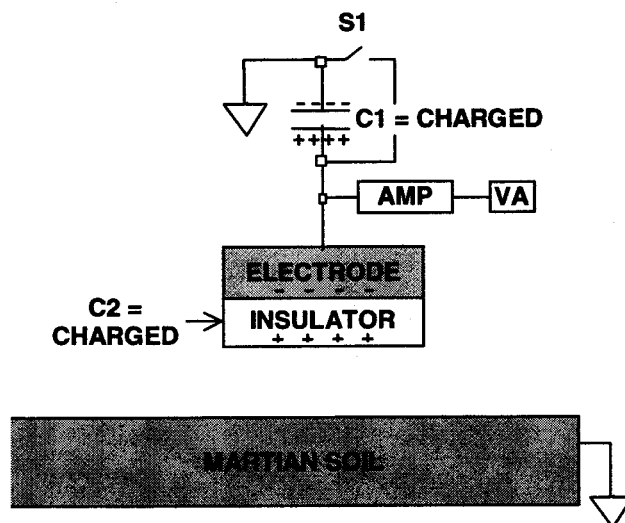
Figure 9: Illustration of electrometer head in the measurement positions above the Martian surface.

A schematic partial cross-section of the MECA sensor is shown in Figure 10. The housing is made of titanium and aluminum. Non-magnetic screws are used since a constituent of the Martian dust is magnetic [15]. Joints are sealed with epoxy to be in compliance with planetary protection.

Resistive heater—The miniature resistive heater is mounted on the sample chamber (Figure 3). During deployment, the chamber is brought into contact with the sample, causing the heater to come into hard contact with the sample surface. The temperature of the heater is then raised to several hundred degrees C, causing adsorbed gas to evolve into the sample chamber. The heater will be procured from commercial sources and will be either metal foil and/or ceramic-based, with a surface contact area of 1 to 5 mm^2. Commercial suppliers for such heaters include ThermoCeramiX LLC, Minco Products, and Electrofilm Mfg. Co.

The oxygen is desorbed from the soil oxidants by using the heater to raise the sample surface temperature to several hundred degrees Centigrade. The oxygen evolution rate will depend on the surface temperature, the surface area of the heated oxidant, and on the bonding energies of the superoxides. Order-of-magnitude calculations, assuming a bond-breaking energy of 1 eV, a surface temperature of 1000 K, and a surface oxidant abundance of less than 1%, indicate that the oxygen evolution rate is approximately 10^{16}/sec. These calculations are

roughly consistent with the Viking oxygen evolution data. Loss of these evolved oxygen molecules is minimized by the fact that the sample chamber makes a good seal with the soil. For a 1-mm gap at the edges of the sample chamber the loss rate is estimated to be less than 10% of the evolution rate.

Fiber Optic Oxygen Sensor—The fiber optic oxygen sensor will be used to *study the evolved oxygen species from the Martian surface*. The oxygen will be evolved as a decomposition product of heated surface oxidants and will have to be detected and measured, not only over the ambient atmospheric background but also over a background of other evolved species as well (see Table 2.). A candidate oxygen sensor is the FOXY fiber optic oxygen sensor manufactured by Ocean Optics Inc (Figure 11). The sensor consists of an optical fiber whose end is coated with a sub-micron thick film containing an immobilized fluorescent ruthenium organic complex.

The ruthenium complex absorbs excitation energy from a blue Light Emitting Diode (LED) with a peak output at 470 nm, and has a fluorescence emission peak near 600 nm. The oxygen detection mechanism operates via quenching of the fluorescence of the ruthenium complex. Collisions of oxygen molecules with fluorophores in their excited states leads to a non-radiative transfer of energy. This is a fairly
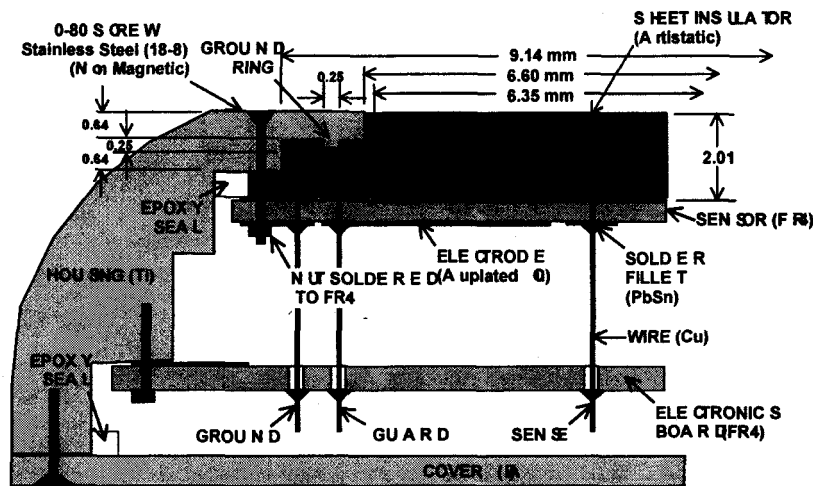
Figure 10. Partial cross-section of the MECA electrometer showing the sensor and insulator sandwich and their connection to the electronics board.

Figure 11. FOXY fiber optic oxygen sensor developed by Ocean Optics Inc.

robust and sensitive detection process and appears to be immune to interferences from other constituents of the Martian atmosphere as well as from other evolved gases such as carbon dioxide and water vapor. The gas species that could potentially interfere with the oxygen measurements are the halogens: F_2, Cl_2 and Br_2. However, none of these gases have been reported as being significant constituents of either the Martian atmosphere or the evolved gases, and therefore should not pose a problem for the detection of evolved oxygen. The response time of the detector is less than 1 second with detection thresholds for the instrument on Earth being at the sub-ppm to ppb level, which is more than adequate for the proposed measurement. For laboratory testing, the commercially available oxygen detection system will be procured. This system was manufactured with the flexibility to measure other gases as well as oxygen and as such weighs over 1 kg, and consumes over 2.6 W. Considerable reductions in mass and power consumption can be achieved by optimizing the system for detecting only oxygen, by replacing the spectrometer (which makes up most of the mass) with two dedicated photodetectors, one for the reflected excitation light and the other for the fluorescence emission.

2.5 ELECTRONICS

The instrument suite will be controlled by a PC based data acquisition and control system running LabView software. The Electrometer electronics will be fabricated based on the design developed for MECA, with the 12-bit A/D incorporated into the acquistion and control electronics via a dedicated microcontroller. The control system currently under development (NASA PIDDP funded) for the AEXS prototype instrument consists of a programmable high-voltage power supply, with four independently programmable and monitored –30 kV modules, a variable voltage electron filament supply based on a miniature high dielectric strength torroidal transformer, and A/D plus D/A boards for monitoring and control.

The electron beam will be modulated and lock-in amplification implemented to increase the signal to noise ratio. The x-ray detector power supply, preamplifier, and shaping amplifier are benchtop units from Amptek, Inc. The x-ray signal is analyzed with a National Instruments high speed DAQ/oscilloscope board configured as a multi-channel analyzer. The CCD data from the optical microscope will be routed via the Matrox frame grabber board to the PC. The electronics boards for the fiber optic oxygen sensor will be used for operation and readout through a standard PC interface. A version of the above electronics systems for a flight instrument proposal would be developed from the laboratory scale electronics systems put together for the purpose of defining the instrument suite. Miniaturization of the various components will build on similar instrumentation developed for flight missions such as the APXS electronics box for Mars Pathfinder and the MECA optical microscope electronics system for the Mars '01 Lander.

2.6 INTEGRATED INSTRUMENT SUITE

The functional block diagram of the integrated instrument suite is shown in Figure 12. The block diagram shows the proposed electronics and power configuration for the individual instruments as well as the nature of the output for each one of the instruments.
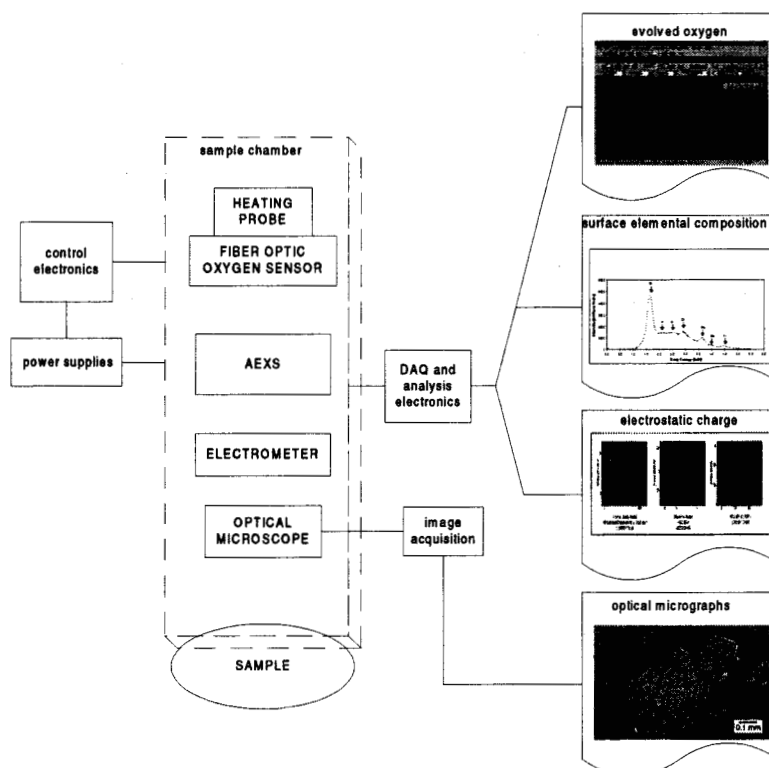

Figure 12. Functional block diagram of the integrated instrument suite

2.7 MASS, POWER AND VOLUME REQUIREMENTS (Table 4)

Table 4. Estimated requirements for a flight version of the instrument suite

Instrument	Component	Mass (g)	Power (W)	Volume (cm^3)
AEXS	Electron gun	25	5	5
	HVPS	325		375
	X-ray detector system	300		250
	Control electronics	125		100
Electrometer	Sensor and electronics	20	.25	10
Fiber optic oxygen sensor	Sensor probe	25	6	10
	LED source	40		25
	Detector and electronics	60		50
	heater	10	6	2
Optical microscope	Camera/lens	80	2	20
	Image acquisition board	100		75
Main electronics	Control and DAQ	250	1	150
	Mechanical components	225	n/a	100
	INSTRUMENT SUITE	**TOTAL** **1,585 g**	**Maximum**[1] **13 W**	**Total** **1,172 cm^3**

[1] The maximum power requirement is for the fiber optic oxygen sensor with the heater and the main electronics operated simultaneously. The instrument suite operating modes only require one instrument operating at a time, leading to less than 13 W required for AEXS, optical microscope, or electrometer operation.

3. INVESTIGATION APPROACH

The primary deliverable for the investigation will be a final report defining a potential flight instrument suite for a 2005 HEDS mission to Mars. The flight instrument suite definition will result from laboratory testing and characterization experiments carried out with prototype instrumentation. Laboratory experiments will utilize instruments in development at JPL combined with modified commercial off-the-shelf instruments. Suite instruments currently being developed by JPL are the AEXS (funded by the NASA PIDDP program) and the electrometer (funded by the MECA-HEDS Mars '01 program). The primary criteria for selection of commercial components will be their miniature size and ruggedness. Since the investigation will be conducted under cost constraints, the emphasis will be on using miniature instruments, which can be readily adapted to meet flight requirements. The following tasks will be accomplished during the course of the investigation.

Modify existing Mars environmental chamber—An environmental chamber will be assembled under NASA-PIDDP funding for AEXS development and characterization. The pressure, composition, and flow rate of gas in the chamber will be precisely controlled. A Residual Gas Analyzer (RGA) will be implemented to monitor H_2O levels, as well as impurities and gas composition. The RGA will allow accurate calibration and threshold limit determination of the fiber optic oxygen sensor system.

Modifications to the chamber will provide electrical and optical feedthroughs for the instrument suite components as well as facilitate installation and manipulation of the sample chamber in the simulated Mars environment.

Define instrument components for laboratory tests— Preliminary specifications of the component instruments will be defined for laboratory operation. Particular attention will be paid to compatibility of these instrument components within the context of the instrument suite. The necessary modifications to these components will be planned at this stage. Miniature sensor heads are required for integration into the sample chamber, the design of which will trade off with the availability constraints of these components. Required threshold detection levels and optimal operating configurations will be determined.

Design and fabricate electrometer head—An electrometer head based on the MECA design will be designed and fabricated for laboratory testing. The design will optimized to fit the instrument suite configuration. Interference and cross-functionality with AEXS operation will be studied.

Procure and modify instrument components—The AEXS prototype and the electrometer will be obtained from existing development efforts at JPL. A commercially available miniature optical microscope with a large working distance, capable of resolving 10 μm particles, will be procured and modified to accept an objective lens of sufficient magnification. A miniature fiber optic oxygen sensor system will be purchased from a vendor such as Ocean Optics, Inc. A miniature ceramic resistive heater will be procured and integrated with the oxygen sensor. Miscellaneous components to modify the existing Mars environmental chamber to accept the instrument suite for testing will be also be procured. Power supplies, electronic diagnostic equipment, and computers will leased from the JPL instrument loan pool for use on this project.

Test and characterize individual prototype instruments—The AEXS instrument prototype testing will be carried out as part of the ongoing PIDDP project. The modified electrometer sensor head will be tested using bench-top electronics developed for the MECA engineering model. The optical microscope will be aligned and tested using the optical calibration facilities at the Microdevices Laboratory (JPL). The resolution and imaging capability of the optical microscope will be tested. The fiber optic oxygen sensor and heater will be installed and tested in the Mars Environmental chamber. The response of the oxygen sensor will be calibrated using the output of the RGA, which will be operated simultaneously with the sensor. Suitable oxidant samples will be identified, procured, and characterized by the Science Co-I.

Design sample chamber—The hemispherical sample chamber has two important functions. It serves as the mount for the component instruments that make up the suite and it determines the instrument/sample configuration. The chamber also functions as a container for oxygen evolved from the sample surface. The dimensions of the individual instrument components and the proposed configuration of the instrument suite will be the driver for the design of the sample chamber. Sealing requirements for the sample chamber will also be considered when developing the design.

Fabrication and integration of the sample chamber into the Mars environmental chamber—Fabrication of the sample chamber will proceed concurrently with the instrument testing task. Following chamber fabrication, the component instruments will be integrated into the sample chamber to form the instrument suite for laboratory testing. The suite will then be installed into the Mars environmental chamber.

Develop instrument control and communication interfaces—This task will develop the electrical, timing, and communication interfaces between the respective instrument suite components. A LabView program will be written for this purpose. The code will be used to control the individual instruments as well as to for data acquisition.

Integrate component instruments and perform instrument suite tests—Following laboratory testing of the individual components, the prototype instrument suite will be assembled. The assembled suite will be integrated into the Mars environmental chamber and tested. Potential functional conflicts and problems with the configuration will be identified and resolved. Cross-functional tests will focus on optimizing the performance of the proposed instrument suite.

Calibrate and characterize the science output of the instrument suite—Following successful cross-functional testing and integration, the individual instrument measurements will be calibrated to insure repeatable and quantitative results. Suitable Martian analog rock and soil samples will either be prepared or acquired from other institutions. Using these samples, the performance of the proposed instrument suite will be critically evaluated to determine the degree to which it is capable of fulfilling HEDS '05 mission requirements.

4. REFERENCES

[1] T. George, "Pump-less microfabricated electron microscope," *NASA New Technology Report NPO-20335*, submitted June 1997.

[2] J. Feldman, T. George and J. Z. Wilcox, "Atmospheric electron x-ray spectrometer," *NASA New Technology Report NPO-20463*, submitted June 1998.

[3] R. Reider, H. Wanke, T. Economou and A. Turkevich, "Determination of the chemical composition of Martian soil and rocks: The alpha proton x-ray spectrometer," *J. Geophysical Res.*, **102**, No, E2, 4027–4044, 1997.

[4] B. C. Clark and A. K. Baird "Martian regolith x-ray analyzer: Test results of geochemical performance," *Geology* **1**, pp. 15–18, 1973.

[5] D. S. Schmidt, R. A. Schmidt and J. D. Dent, "Electrostatic force on saltating sand," *J. Geophys. Res.* **103**, 8997–9001, 1998.

[6] R. Greeley and J. D. Iversen, *Wind as a Geological Process on Earth, Mars, Venus and Titan*, Cambridge Univ. Press, New York, 1985.

[7] B. Walch, M. Horanyi and S. Robertson, "Measurement of the charging of individual dust grains in a plasma," *IEEE Trans. Plasma Sci.* **22**, 97–102, 1994.

[8] J. A. Cross, *Electrostatics: Principles, Problems and Applications*, Adam Hilger, Bristol, England, 1987, pp. 343–345.

[9] R. Greeley and R. Leach, "A preliminary assessment of the effects of electostatics on aeolian processes," Rep. Planet. Geol. Program, 1977–1978, *NASA TM 79729*, 236–237, 1978.

[10] R. Meano, R. Naruse, *et al*, "Wind-tunnel experiments on blowing snow," *Ann. Glaciol.*, **6**, 63–67, 1985.

[11] A. P. Zent and C. P. McKay, "The chemical reactivity of the Martian soil and implications for future missions," *Icarus* **108**, 146–157, 1994.

[12] A. P. Zent, "On the thickness of the oxidized layer of the Martian regolith," *J. Geophys. Res.* **103**, 31, 491–498, 1998.

[13] M. Buehler, L-J. Cheng, O. Orient, R. Gompf, J. Bayliss, J. Rauwerdink and J. Marshall, "MECA electrometer: Initial experimental results, Fifth Int. Conf. on Mars," July 18–23, 1999, Pasadena, CA.

[14] M. Buehler, L-J. Cheng, O. Orient, M. Thelen, R. Gompf, J. Bayliss and J. Rauwerdink, "MECA electrometer: Initial calibration experiments," submitted for publication, Institute of Physics, Electrostatics '99 Conference, 1999, Cambridge, England.

[15] M. B. Madsen, *et al*, "The magnetic properties experiments on Mars Pathfinder," *J. Geophys. Res.* **104**, 8761–8779, 1999.

5. ACKNOWLEDGEMENTS

6. RESUMES

Thomas George is the Supervisor of the MEMS Technology Group at the Device Research and Application Section at JPL. He invented the concept of a pump-less microfabricated electron microscope and is a co-inventor with J.Z. Wilcox and J. Feldman of a miniature ring orbitron ion pump as well as the AEXS concept. He received his PhD in Materials Science from the University of California at Berkeley. As a postdoctoral researcher at UCB and Intel Corp., he was involved in the characterization of lattice-mismatched GaAs heteroepitaxial systems and metal-semiconductor interfaces using high resolution and analytical TEM. As a visiting researcher at the Nagoya Institute of Technology, he worked on GaAs and high Tc superconducting materials, set up and trained researchers to operate HRTEM facilities, and performed materials research of epitaxial Si, GaAs, and GaN for detector applications. He joined JPL in 1990, where he set up and operated a HRTEM laboratory and managed tasks aimed at the development of AlGaN-based, solar-blind, ultraviolet detectors. He has successfully commercialized a JPL-developed, bulk Si-micromachined tunneling infrared detector. He currently manages the MEMS Technology Group with diverse MEMS-based projects and is also the task manager of a program entitled "Development of MEMS-based in situ Microinstruments". The aim of this program is to develop microinstruments for planetary exploration, and as a part of that program, he is also involved in the development of a MEMS-based NMR spectrometer, micromachined broadband light sources and an optically detected airfoil pressure sensor. Dr. George has hands-on experience in Si-based MEMS processing and assembly and characterization techniques such as SIMS, SEM, AFM, ESCA and Auger spectroscopy. He has authored/co-authored over 40 archival journal publications and holds 3 U.S. patents.

Jason Feldman is a member of the technical staff at the Device Research and Application Section at JPL. He is the cognizant engineer for the MECA patch plate dust adhesion experiment to be flown on the '01 Mars Lander. He invented the AEXS instrument in collaboration with T. George and J. Z. Wilcox. He received his BA in Physics from the University of California at Berkeley. At Lawrence Berkeley National Laboratory, he worked with Professor Paul Richards on the Millimeter Anisotropy Experiment (MAX). In addition to his key project, the design, fabrication, and implementation of high speed radiation-hard serial data communications systems for a high altitude NASA-NSBF balloon-borne telescope, he was responsible for setting up a new laboratory and calibration facility, optimization of the analog electronics, and coordination of systems compatibility with collaborators. He joined Caltech in 1998 as an assistant engineer with Professor Axel Scherer, and JPL in 1999. He is a co-inventor with J.Z. Wilcox and T. George of a miniature ring orbitron ion pump. He develops new instruments and sensors for in-situ planetary exploration, bringing them from the conceptual phase to readiness for research. Jason brings a wealth of practical experience in the area of design, fabrication and testing of vacuum, mechanical and electronic, cryogenic, and gaseous systems.

Nathan Bridges is a scientist at JPL. He received his PhD in geology from the University of Massachusetts, Amherst, in 1997. His dissertation "The origin of Venusian steep-sided domes" was in the area of planetary geology, volcanology, igneous petrology, remote sensing, and geophysics. He came to Caltech/JPL as a Postdoctoral Scholar to join a team studying the spectral properties of rocks and soils and the physical weathering of rocks at the Pathfinder landing site. He was a Co-I on a MED grant studying the South polar region of Mars in support of site selection for the Mars Polar Lander mission. He was also part of the landing site selection team for Mars '01, '03, and '05 missions, and he was a PI on Mars Data Analysis NASA Program "Ventifacts and Rock Spectral Properties at the Mars Pathfinder Landing Site." Dr. Bridges also worked as a geologist on lunar and Martian studies with the US. Geological Survey, where he received Outstanding Employee and Dwornik Best Student Paper Award at Lunar and Planetary Science Conference in 1992. He is the co-author of 20 articles in refereed journals, and of over 50 abstracts.

Martin Buehler received the BSEE and MSEE from Duke University in 1961 and 1963, respectively and the Ph.D. in EE from Stanford University in 1966 with the specialization in Solid State Electronics. He

worked at Texas Instruments for six years, at National Bureau of Standards (now NIST) for eight years, and since 1981 has been at the Jet Propulsion Laboratory. In 1978, he was awarded the Department of Commerce's Silver Metal for creative contributions to semiconductor metrology and in 1985 he received the NASA Exceptional Achievement Medal for leadership in the design of microelectronic test structures. At JPL he is a Senior Research Scientist in the Microdevices Laboratory. He is the Principal Investigator for the Clementine RRELAX, which flew in 1994, and MAPEX, which landed on Mars in 1997. He has provided total radiation dosimeters for the CRRES, MSX, and STRV experimental spacecrafts and Telstar and Intelsat communication satellites. He has successfully flown his RADMON (Radiation Monitor) and test devices in space eleven times. He is co-Principal Investigator for the Electronic Nose air quality monitor, which flew on STS-95 with John Glenn and is currently technical lead for the MECA/Electrometer for Mars '01. He is also co-lead for In situ Instruments and MEMS, New Millennium Program. He has authored over 80 papers and holds seven patents on novel microelectronic devices and test structures. He is co-founder of the IEEE sponsored International Conference on Microelectronic Test Structures and has served as its General Chairman, Technical Chairman, Finance Chairman, and Tutorial Chairman. He's served as editor for the Nuclear and Space Radiation Effects Conference December 1993 issue. Martin is a member of the IEEE Electron Devices Society and Nuclear Science Society.

Howard Rockstad is a Senior Engineer in the Device Research and Applications Section, 3460, at JPL. He has worked with MEMS devices at JPL for several years. Prior to his work at JPL, and with relevance to AEXS application in the Grand Challenge program, he had five years of electron probe microanalysis experience with Atlantic Richfield, where he also led analytical instrument evaluation for a new corporate laboratory. He also provided analytical and experimental support for development of electron beam accessed high-capacity computer memories in the Micro-Bit Division of Control Data Corporation. Prior to that he performed amorphous semiconductor research at Corning Glass Works and Energy Conversion Devices, Inc. He received his Ph.D. in Physics from the University of Illinois in Urbana.

Jaroslava Z. Wilcox is a Member of the Technical Staff at the Device Research and Applications Section at JPL. She is a co-inventor with T. George and J. Feldman of a miniature ring orbitron ion pump for

electron microscope applications as well as the AEXS concept. She received her PhD in Solid State Physics at the University of California at Los Angeles. She taught at Tufts University for two years, and in 1974 joined TRW Space Systems where she worked on inter-modulation processes in coaxes, millimeter-wave imaging, a novel phased array SAW RF spectrum analyzer, and mostly, in electro-optics. She was the principal investigator of QWIP IR sensors program, was the program manager of the program for the development of GaAlAs solar cells, and a task leader for laser-induced annealing and several diode laser development programs. She designed and analyzed performance of MQW diode lasers and arrays of diode lasers for coherent emission and for high power (including heat removal and powering) for pumping solid-state lasers. Dr. Wilcox joined JPL in 1990, where she provided design and analytical support for the development of vibrational micro-gyroscope and other MEMS devices. More recently, she was involved in the calibration of the evolved water experiment for DS2 New Millenium mission, and her current research is in the area of micro-instruments for in-situ observations. She received several technical achievement awards and was listed in "American Men and Women in Science" and "Who is Who in Technology Today." She has also published over 90 papers in refereed journals and has given several invited and numerous contributed talks at professional meetings. In addition, she holds and has applied for several patents in the area of solid-state devices.